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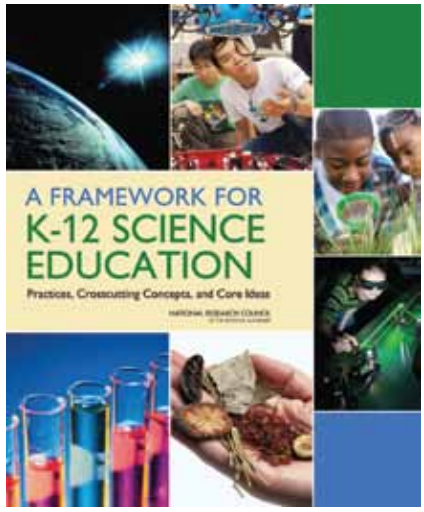
Scientific and Engineering Practices in K–12 Classrooms

Understanding *A Framework for K–12 Science Education*



by Rodger W. Bybee

This morning I watched *Sesame Street*. During the show, characters "acted like engineers" and designed a boat so a rock could float. In another segment, children asked questions and made predictions about the best design for a simple car. They then built a model car and completed an investigation to determine which design worked best when the cars went down inclined planes. Children also learned that a wider base provided stability for a tower. And, among other segments, the children counted from 1 to 12 and explored the different combinations of numbers that equaled 12. Bert and Ernie had to move a rock and ended up "inventing" a wheel. These segments exemplify the science, technology, engineering, and mathematics (STEM) theme that *Sesame Street* is introducing in the show's 42nd season.

What, you ask, does this have to do with science and engineering practices in K–12 classrooms? The producers of *Sesame Street* decided that STEM practices were important enough that they are using them as substantive themes for the season, if not longer. Children watching *Sesame Street* will have been introduced to practices such as asking questions and defining problems; developing and using models; planning and carrying out investigations; analyzing and interpreting data; using mathematics; constructing explanations and designing solutions; engaging in arguments using evidence; and obtaining, evaluating, and communicating information. True, these are sophisticated statements of practices, but many students will be introduced to them when they enter elementary classrooms.

In this article, I present the science and engineering practices from the recently released *A Framework for K–12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (NRC 2011). I recognize the changes implied by the new framework, and eventually a new generation of science education standards will present new perspectives for the science education community. I am especially sensitive to the challenges for those students in teacher preparation programs and classroom teachers of science at all levels. Questions such as "Why practices and why not inquiry?" and "Why science *and* engineering?" are reasonable, and I will discuss them later. But to provide background and context, I first discuss the practices.

Understanding and applying the science and engineering practices

This section further elaborates on the practices and briefly describes what students are to know and be able to do, and how they might be taught. Figures 1 through 8 are adapted from the National Research Council (NRC) framework, with changes for clarity and balance. I have maintained the substantive content.

Even before elementary school, children ask questions of each other and of adults about things around them, including the natural and designed world. If students develop the practices of science and engineering, they can ask better questions and improve how they define problems. Students should, for example, learn how to ask questions of each other, to recognize the difference between questions and problems, and to evaluate scientific questions and engineering problems from other types of questions. In upper grades, the practices of asking scientific questions and defining engineering problems advance in subtle ways such as the form and function of data used in answering questions and the criteria and constraints applied to solving problems.

In the lower grades, the idea of scientific and engineering models can be introduced using pictures, diagrams, drawings, and simple physical models such as airplanes or cars. In upper grades, simulations and more sophisticated

Figure 1. Asking questions and defining problems

Science begins with a question about a phenomenon such as "Why is the sky blue?" or "What causes cancer?" A basic practice of the scientist is the ability to formulate empirically answerable questions about phenomena to establish what is already known, and to determine what questions have yet to be satisfactorily answered.	**Engineering** begins with a problem that needs to be solved, such as "How can we reduce the nation's dependence on fossil fuels? or "What can be done to reduce a particular disease? or "How can we improve the fuel efficiency of automobiles? A basic practice of engineers is to ask questions to clarify the problem, determine criteria for a successful solution, and identify constraints.

Figure 2. Developing and using models

Science often involves the construction and use of models and simulations to help develop explanations about natural phenomena. Models make it possible to go beyond observables and simulate a world not yet seen. Models enable predictions of the form "if...then... therefore" to be made in order to test hypothetical explanations.	**Engineering** makes use of models and simulations to analyze extant systems to identify flaws that might occur, or to test possible solutions to a new problem. Engineers design and use models of various sorts to test proposed systems and to recognize the strengths and limitations of their designs.

Figure 3. Planning and carrying out investigations

Scientific investigations may be conducted in the field or in the laboratory. A major practice of scientists is planning and carrying out systematic investigations that require clarifying what counts as data and in experiments identifying variables.	**Engineering investigations** are conducted to gain data essential for specifying criteria or parameters and to test proposed designs. Like scientists, engineers must identify relevant variables, decide how they will be measured, and collect data for analysis. Their investigations help them to identify the effectiveness, efficiency, and durability of designs under different conditions.

Figure 4. Analyzing and interpreting data

Scientific investigations produce data that must be analyzed in order to derive meaning. Because data usually do not speak for themselves, scientists use a range of tools—including tabulation, graphical interpretation, visualization, and statistical analysis—to identify the significant features and patterns in the data. Sources of error are identified and the degree of certainty calculated. Modern technology makes the collection of large data sets much easier providing secondary sources for analysis.	**Engineering investigations** include analysis of data collected in the tests of designs. This allows comparison of different solutions and determines how well each meets specific design criteria—that is, which design best solves the problem within given constraints. Like scientists, the engineers require a range of tools to identify the major patterns and interpret the results. Advances in science make analysis of proposed solutions more efficient and effective.

Figure 5. Using mathematics and computational thinking

In **science,** mathematics and computation are fundamental tools for representing physical variables and their relationships. They are used for a range of tasks such as constructing simulations; statistically analyzing data; and recognizing, expressing, and applying quantitative relationships. Mathematical and computational approaches enable prediction of the behavior of physical systems along with the testing of such predictions. Moreover, statistical techniques are also invaluable for identifying significant patterns and establishing correlational relationships.	In **engineering,** mathematical and computational representations of established relationships and principles are an integral part of the design process. For example, structural engineers create mathematical-based analysis of designs to calculate whether they can stand up to expected stresses of use and if they can be completed within acceptable budgets. Moreover, simulations provide an effective test bed for the development of designs as proposed solutions to problems and their improvement, if required.

Figure 6. Constructing explanations and designing solutions

The goal of **science** is the construction of theories that provide explanatory accounts of the material world. A theory becomes accepted when it has multiple independent lines of empirical evidence, greater explanatory power, a breadth of phenomena it accounts for, and has explanatory coherence and parsimony.	The goal of **engineering design** is a systematic solution to problems that is based on scientific knowledge and models of the material world. Each proposed solution results from a process of balancing competing criteria of desired functions, technical feasibility, cost, safety, aesthetics, and compliance with legal requirements. Usually there is no one best solution, but rather a range of solutions. The optimal choice depends on how well the proposed solution meets criteria and constraints.

conceptual, mathematical, and computational models may be used to conduct investigations, explore changes in system components, and generate data that can be used in formulating scientific explanations or in proposing technological solutions.

Planning and carrying out investigations should be standard experiences in K–12 classrooms. Across the grades students develop deeper and richer understandings and abilities as they conduct different types of investigations, use different technologies to collect data, give greater attention to the types of variables, and clarify the scientific and/or engineering contexts for investigations.

Both science and engineering involve the analysis and interpretation of data. In lower grades, students simply record and share observations though drawings, writing, whole numbers, and oral reports. In middle and high school, students report relationships and patterns in data, distinguish between correlation and causation, and compare and contrast independent sets of data for consistency and confirmation of an explanation or solution.

The overlap of these practices with the next practices, using mathematical and computational thinking, is significant. Although both of these sets of practices can be completed with simulated data, it is beneficial for students to actually experience the practices of collecting, analyzing, and interpreting data and in the process apply mathematical and computational thinking.

In the early grades, students can learn to use appropriate instruments (e.g., rulers and thermometers) and their units in measurements and in quantitative results to compare proposed solutions to an engineering problem. In upper grades, students can use computers to analyze data sets and express the significance of data using statistics.

Students can learn to use computers to record measurements, summarize and display data, and calculate relationships. As students progress to higher grades, their experiences in science classes should enhance what they learn in math class.

The aim for students at all grade levels is to learn how to use evidence to formulate a logically coherent

Figure 7. Engaging in argument from evidence

In **science,** reasoning and argument are essential for clarifying strengths and weaknesses of a line of evidence and for identifying the best explanation for a natural phenomenon. Scientists must defend their explanations, formulate evidence based on a solid foundation of data, examine their understanding in light of the evidence and comments by others, and collaborate with peers in searching for the best explanation for the phenomena being investigated.	In **engineering,** reasoning and argument are essential for finding the best solution to a problem. Engineers collaborate with their peers throughout the design process. With a critical stage being the selection of the most promising solution among a field of competing ideas. Engineers use systematic methods to compare alternatives, formulate evidence based on test data, make arguments to defend their conclusions, critically evaluate the ideas of others, and revise their designs in order to identify the best solution.

Figure 8. Obtaining, evaluating, and communicating information

Science cannot advance if scientists are unable to communicate their findings clearly and persuasively or learn about the findings of others. A major practice of science is thus to communicate ideas and the results of inquiry—orally; in writing; with the use of tables, diagrams, graphs and equations; and by engaging in extended discussions with peers. Science requires the ability to derive meaning from scientific texts such as papers, the internet, symposia, or lectures to evaluate the scientific validity of the information thus acquired and to integrate that information into proposed explanations.	**Engineering** cannot produce new or improved technologies if the advantages of their designs are not communicated clearly and persuasively. Engineers need to be able to express their ideas orally and in writing; with the use of tables, graphs, drawings or models; and by engaging in extended discussions with peers. Moreover, as with scientists, they need to be able to derive meaning from colleagues' texts, evaluate information, and apply it usefully.

explanation of phenomena and to support a proposed solution for an engineering problem. The construction of an explanation or solution should incorporate current scientific knowledge and often include a model. These practices along with those in Figure 1 differentiate science from engineering.

In elementary grades, students might listen to two different explanations for an observation and decide which is better supported with evidence. Students might listen to other students' proposed solutions and ask for the evidence supporting the proposal. In upper grades, students should learn to identify claims; differentiate between data and evidence; and use logical reasoning in oral, written, and graphic presentations.

In elementary grades, these practices entail sharing scientific and technological information; mastering oral and written presentations; and appropriately using models, drawings, and numbers. As students progress, the practices become more complex and might include preparing reports of investigations; communicating using multiple formats; constructing arguments; and incorporating multiple lines of evidence, different models, and evaluative analysis.

With this introduction and overview of science and engineering practices, I turn to some of the questions engaged by a shift in teaching strategies and learning outcomes. Although science teachers have many questions, the next sections discuss two questions that seem prominent: "Why *practices*?" and "Why *engineering*?"

Why *practices*?

Science teachers have asked, "Why use the term *practices*? Why not continue using *inquiry*?" These are reasonable questions. A brief history will provide the context for an answer.

One major innovation in the 1960s reform movement was the introduction of the *processes* of science as a replacement for the *methods* of science. The processes of science shifted the emphasis from students' memoriz-

ing five steps in the scientific method to learning specific and fundamental processes such as observing, clarifying, measuring, inferring, and predicting. To complement this new emphasis, the new reformed instructional materials incorporated activities, laboratories, and investigations that gave students opportunities to learn the processes of science while developing an understanding of the conceptual structure of science disciplines.

During the period 1960–1990, interest and support grew for *scientific inquiry* as an approach to science teaching that emphasized learning science concepts and using the skills and abilities of inquiry to learn those concepts.

This change toward scientific inquiry was expressed by leaders such as Joseph Schwab and Paul Brandwein and publications such as *Science for All Americans* (Rutherford and Ahlgren 1989). In the 1990s, scientific inquiry was fundamental to the *Benchmarks for Science Literacy* (AAAS 1993) and the *National Science Education Standards* (NRC 1996). Along with *Inquiry and the National Science Education Standards* (NRC 2000), these two publications had a significant influence on state standards and the place of inquiry in school science programs. It is important that scientific inquiry expanded and improved the earlier processes of science and provided richer understanding of science, a set of cognitive abilities for students, and more effective teaching strategies. One should note that the reforms toward the *processes of science* and *scientific inquiry* did result in greater emphasis on the use of activities and investigations as teaching strategies to learn science concepts. However, scientific inquiry has not been implemented as widely as expected.

During the 15 years since the release of the standards, researchers have advanced our knowledge about how students learn science (Bybee 2002; Donovan and Bransford 2005) and the way science functions. Advances in these and other areas have been synthesized in *Taking Science to School* (Duschl, Schweingruber, and Shouse 2007) and *Ready, Set, Science!* (Michaels, Shouse, and Schweingruber 2008). These two publications had a significant influence on the Framework.

Taking Science to School describes four proficiencies that link the content and practices of science. Students who are proficient in science

- know, use, and interpret scientific explanations of the natural world;
- generate and evaluate scientific evidence and explanations;
- understand the nature and development of scientific knowledge; and
- participate productively in scientific practices and discourse. (Duschl, Schweingruber, and Shouse 2007, p. 2)

The following quote from *Ready, Set, Science!* builds on these proficiencies and presents an answer to the question, "Why practices?"

Throughout this book, we talk about "scientific practices" and refer to the kind of teaching that integrates the four strands as "science as practice." Why not use the term "inquiry" instead? Science practice involves doing something and learning something in such a way that the doing and learning cannot really be separated. Thus, "practice" . . . encompasses several of the different dictionary definitions of the term. It refers to doing something repeatedly in order to become proficient (as in practicing the trumpet). It refers to learning something so thoroughly that it becomes second nature (as in practicing thrift). And it refers to using one's knowledge to meet an objective (as in practicing law or practicing teaching). (Michaels, Shouse, and Schweingruber 2008, p. 34)

Scientific inquiry is one form of scientific practice. So, the perspective presented in the framework is not one of replacing inquiry; rather, it is one of expanding and enriching the teaching and learning of science. Notice the emphasis on teaching strategies aligned with science practices. When students engage in scientific practices, activities become the basis for learning about experiments, data and evidence, social discourse, models and tools, and mathematics and for developing the ability to evaluate knowledge claims, conduct empirical investigations, and develop explanations.

Why *engineering*?

Again, a brief history establishes a context for the inclusion of engineering practices. In the 1960s, technology and engineering were marginalized in the U.S. science curriculum (Rudolph 2002). This said, the era of curriculum reform in the United States did produce one program, *The Man Made World*, developed by the Engineering Concepts Curriculum Project (1971). However, technology was included in other countries (Black and Atkin 1996; Atkin and Black 2003). Publication of *Science for All Americans* (Rutherford and Ahlgren 1989) included chapters on "the nature of technology" and "the Designed World." This reintroduction of technology and engineering was further advanced by their inclusion in the *Benchmarks for Science Literacy* (AAAS 1993) and *National Science Education Standards* (NRC 1996). Technology gained further support with the publication of the *Standards for Technological Literacy* (ITEA 2000).

In the early 21st century, the acronym STEM has emerged as a description of many and diverse educational initiatives. The *T* and *E* in STEM represent *technology* and *engineering*.

As the reader no doubt recognized in the eight figures, the practices of science and engineering overlap in many ways. With the exception of their goals—science proposes questions about the natural world and proposes answers in the form of evidence-based explanations, and engineering identifies problems of human needs and aspirations and proposes solutions in the form of new products and processes—science and engineering practices are parallel and complementary.

So, there is a need for science teachers and those in teacher education programs to recognize the similarities and differences between science and technology as disciplines and subsequently the practices that characterize the disciplines.

At elementary levels, there is good news. Many activities that are already in the curriculum are based on engineering problems. Building bridges, dropping eggs, and (as we saw in the opening on *Sesame Street*) designing model cars are all examples of engineering in elementary school programs. Unfortunately, these engineering problems and subsequent practices are often referred to erroneously as science. With a clarification of terms and a continuation of the activities, elementary teachers can introduce science and engineering practices without significant additions to the curriculum. And, as value added, the engineering problems are highly motivating for the students at all grade levels.

At the middle and high school levels, science teachers can begin with the technologies already used—microscopes, telescopes, and computers—as examples of the relationship between science and technology. In addition, there are examples clearly embedded in the practices of science and engineering. Here, I would also add the value of the history of science to show the role of technology and engineering and their contributions to the advance of scientific knowledge. An excellent contemporary example of the advance of science that is due to technology and engineering is the Hubble Space Telescope and its potential successor, the James Webb Space Telescope.

Complementing goals

This article explores one aspect of the new NRC framework—science and engineering practices—in greater depth. Although the NRC report is a framework and not standards, it is prudent for those in the science and technology education community to begin preparing for the new standards.

Because science and engineering practices are basic to science education and the change from inquiry to practices is central, this innovation for the new standards will likely be one of the most significant challenges for the successful implementation of science education standards. The brief discussion that follows is based on the prior description of science and engineering practices in Figures 1 through 8.

The relationship between science and engineering practices is one of complementarity. Given the inclusion of engineering in the science standards and an understanding of the difference in aims, the practices complement one another and should be mutually reinforcing in curricula and instruction.

The shift to practices emerges from research on how students learn and advances our understanding of how science progresses. The new emphasis on practices includes scientific inquiry and goes beyond what science teachers have realized based on the 1990s standards. Indeed, as I have noted, there is overlap with the 1996 standards, for example.

The new emphasis on practices reinforces the need for school science programs to actively involve students through investigations and, in the 21st century, digitally based programs and activities. Hands-on and laboratory work should still contribute to the realization of practices in science classrooms. As we saw in the earlier quote from *Ready, Set, Science!,* there is a reasonable assumption that across the K–12 continuum the abilities and understandings of science and engineering practices will progressively get deeper and broader.

Science and engineering practices should be thought of as both learning outcomes and instructional strategies. They represent both educational ends and instructional means. First, students should develop the abilities described in the practices, and they should understand how science knowledge and engineering products develop as a result of the practices. Second, as instructional strategies, the practices provide a means to the learning outcomes just described and other valued outcomes such as students' understanding of the core ideas and crosscutting concepts expressed in the framework. In brief, the practices represent one aspect of what students are to know, what they are able to do, and how they should be taught. Granted, this is a large order, but from the perspective of K–12, teachers will have 13 years to facilitate students' attaining the goals.

To conclude, watching the children and characters on *Sesame Street* gave me confidence that the new challenges are achievable and that K–12 science education will have a generation of boys and girls ready to engage in and learn from science and engineering practices. Preparing for the next generation of science education standards will help science teachers attain the higher aspiration of this and future generations.

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